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CMB as a possible new tool to study the dark baryons in galaxies

F. De Paolis, G. Ingrosso, A.A. Nucita, D. Vetrugno
Dipartimento di Fisica, Università del Salento, Via per Arnesano, I-73100, Lecce, Italy and INFN, Sezione di Lecce, Via per Arnesano, I-73100, Lecce, Italy
E-mail: francesco.depaolis@le.infn.it

V.G. Gurzadyan, A.L. Kashin, H.G. Khachatryan, S. Mirzoyan
Yerevan Physics Institute and Yerevan State University, Yerevan, Armenia

Ph. Jetzer
Institute für Theoretische Physik, Universität Zürich, Winterthurerstrasse 190, 8057 Zürich, Switzerland

A. Qadir
Center for Advanced Mathematics and Physics, National University of Sciences and Technology, H-12, Islamabad, Pakistan

Abstract. Baryons constitute about 4% of our universe, but most of them are missing and we do not know where and in what form they are hidden. This constitute the so-called missing baryon problem. A possibility is that part of these baryons are hidden in galactic halos. We show how the 7-year data obtained by the WMAP satellite may be used to trace the halo of the nearby giant spiral galaxy M31. We detect a temperature asymmetry in the M31 halo along the rotation direction up to about 120 kpc. This could be the first detection of a galactic halo in microwaves and may open a new way to probe hidden baryons in these relatively less studied galactic objects using high accuracy CMB measurements.

1. Introduction

We have entered in a new era of high precision cosmology and it is clear by primordial nucleosynthesis constraints and by the results from the power spectrum of the CMB produced by the 7-years data of WMAP satellite that our universe is composed of $\simeq 73\%$ of dark energy (DE), $\simeq 23\%$ of non-baryonic dark matter (DM) and for only $\simeq 4\%$ by baryons. About baryons, we know that about 10% of them are in stars (i.e. in the visible part of galaxies); the hot gas in galaxies and galaxy clusters accounts for another $20-30\%$ of baryons; but about $60-70\%$ of all baryons are missing and is not known where and in which form they are hidden [1]. A possibility is that these baryons are contained in the so-called cosmic filaments in the form of a

[1] Observations also show that galaxies are missing most of their baryons with respect to the cosmological baryon/matter ratio (see e.g. [1, 2, 3]).

warm-hot intergalactic medium (see e.g. [4, 5, 6, 7]). However, it is unlikely that all the missing baryons are confined in the cosmic filaments and, actually, there are many reasons to believe that a non-negligible amount of these hidden baryons are in galactic halos (see below in this section) or even in the galactic disk (see e.g. [8] and references therein) [2].

A rather clear piece of evidence for the existence of large amounts of gas around galaxies is the widespread detection of absorption lines in front of quasars, the so-called Ly-α forest, that show hundreds of absorption systems along a single line of sight. Also damped Ly-α systems with hydrogen columns density larger than about 10^{20} cm^{-2} are associated with galaxies and both systems imply that galaxies at high redshift ($\sim 2-2.5$) would have huge gas halos around them. Where is all that gas now? One possibility is that it has been expelled from galaxies during the first chaotic phase of star formation into the cosmic filaments. However, that might have happened only in part, leaving nowadays some of that gas around galactic disks.

There is further evidence that there is some amount of gas in galactic halos, and in particular in that of our galaxy: the problem is to measure how much it is. That is, obviously, not so easy. Let us briefly discuss some of this evidence.

Galaxies seem to evolve along the Hubble sequence from Sc type, characterized by small bulges and open spiral arms to Sa, characterized by larger bulges and tighter spirals. During this evolution the M/L ratio, which is a measure of the amount of dark matter, decreases (while the number of stars increases) implying that part of the dark matter should transform into stars and that means that part of the dark matter should consist of baryons in gaseous form. Moreover, star-forming disk galaxies similar to our Milky Way, should exhaust their cold gas reservoir (necessary to make stars) within a few Gyrs unless it is replenished in some way [10, 11]. Numerical simulations (see e.g. [12]) indeed show that galaxies like the Milky Way convert about 1 $M_{\odot}$ yr^{-1} of gas into stars while their gas content remains approximately unchanged. The reservoir of the accretion material is as yet unidentified but it goes without saying that it should come from the region that surrounds the galactic disks and might even reside in the intergalactic medium (see [13] for a discussion about the cooling mechanisms of the hot intergalactic gas). In any case, a gas accretion rate of about 1 $M_{\odot}$ yr^{-1} for M31/Milky Way galaxies onto their galactic disks is compulsory (see also [14]).

The wealth of data in the last two decades show that there is good evidence for extra-planar gas around the Milky Way and other galaxies and it is detected in all gaseous phases: neutral, warm atomic, molecular and hot X-ray emitting gas. Since about a decade we know that around the Milky Way and Andromeda (M31) galaxies there is a population of high-velocity clouds (HVCs) that extends up to $10-20$ kpc and are not seen beyond about 50 kpc [15]. There are also intermediate-velocity clouds (IVCs) with a vertical scale height of $4-5$ kpc and a total mass about $3-4\times10^{8}$ $M_{\odot}$, forming a population separated with respect to that of the HVCs. The innermost halo clouds show a metallicity that is about half of the solar one and this favors the Galactic fountain model for its origin in which hot gas is ejected out of the galactic disk, cools down and falls back onto the disk (see e.g. [16]). As far as HVCs are concerned, since generally only the radial velocity can be estimated for these objects and distance information are sparse and not well known, a closed theory about their origin is not available today. One possibility is that they represent metal poor gas from the intergalactic space falling onto the galactic disk [17], the other is that they represent the remnant of the galactic halo formation.

Also around the Andromeda galaxy (M31) deep radio synthesis observations has shown the presence of gas clouds within about 50 kpc. These clouds, which are the analogue of the HVCs, have size of about 1 kpc and mass $\simeq 10^{5}$ $M_{\odot}$ [18]. The total mass in HVCs is about 10^{8} $M_{\odot}$ [14].

[2] The first to suggest the concept of the presence of the gas above the disk of the Milky Way was Spitzer in his remarkable paper of 1956 [9] where he also discussed the nature and the possible evolution of the gas eventually present there.

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It also seems that a dilute gas halo at a temperature $\sim 10^6$ K is present around some spiral galaxies. Elliptical galaxies (and particularly bright ellipticals), as is well known, do contain large amount of hot diffuse gas emitting in X-rays (see e.g. [19] and references therein). For spirals, evidence is much less convincing. A difficulty in this respect is that the emission measure scales with the square of the electron density and once the galaxy surface brightness drops to the level of the X-ray background (mainly due to the Milky Way) further detection is impossible. That is the reason why the size of the X-ray emitting gas around spiral galaxies is very poorly constrained. Interestingly enough, very recently a hot gaseous halo has been detected by XMM-Newton satellite towards UGC12591, the fastest rotating spiral galaxy [20], up to a distance of about 110 kpc from the galaxy center. Combining the X-ray data with near-IR and radio measurements it has been found that the baryon mass fraction in this galaxy is about $3-4\%$ (in particular the baryon mass within about 500 kpc is $\simeq 5.9\times10^{11}\ M_\odot$ while the total mass, estimated using the galaxy rotation curve, is found to be $\simeq 2.7\times10^{13}\ M_\odot$). This would imply that the majority of the missing baryons in spiral galaxies does not reside in their hot gas halos [3].

Indeed, after the detection of the first microlensing events towards the LMC [22, 23] [4] a model was proposed for the formation of MACHOs (Massive Astrophysical Compact Halo Objects) in the galactic halo [44, 45]. Actually, this model naturally emerges from the present-day understanding of the globular cluster formation. Indeed, the Fall-Rees theory for the formation of globular clusters [46] predicts, without any further assumption, that dark clusters made of brown dwarfs and cold gas clouds should lurk in the galactic halo at galactocentric distances larger that $10-20$ kpc. Accordingly, the inner halo is populated mainly by globular clusters, whereas the outer galactic halo should be dominated by dark clusters populated by MACHOs and cold gas clouds [5]. The gas clouds in the dark clusters should be very cold, with a temperature very close to that of the CMB, should have sub-solar mass and size about that of the Solar System (for details see [53]).

A novel way of investigating the amount and distribution of the dark baryons in the galactic halos, and in particular in that around the M31 galaxy is discussed in the next section. This method deals with the use of CMB data (at present the 7-year WMAP data) to trace galactic disks and halos.

2. The temperature asymmetry in the M31 halo by the 7-year WMAP data

Galactic disks are well studied objects in all wavelengths and give important information on the mass distribution within and around galaxies [54]. On the other hand, galactic halos are relatively less studied structures and there are still many ambiguities not only in the main halo constituents, but also in the basic properties such as, in particular, the rotation.

The degree to which galactic halos rotates with respect to the disks is a relevant and difficult

[3] The fact that galactic halos do not contain much hot baryons is also confirmed by the dispersion measure of pulsars in the LMC [21].

[4] Microlensing observations conducted since two decades both towards the Galactic bulge and the Magellanic Clouds by MACHO, EROS and OGLE Collaborations have shown that a (probably) not-negligible fraction (about $5-20\%$) of the halo dark matter may be made by MACHOs (see e.g. [24, 25, 26]) although this result as well as the estimation of the average MACHO mass implied by observations depends on the specific adopted halo model (see e.g. [27, 28]). Pixel-lensing observations towards the M31 galaxy have been conducted by several collaborations leading to the discovery of more than 35 events [29, 30, 31, 32, 33, 34, 35] up to now (one of which even showed the presence of an exoplanet in Andromeda galaxy [36, 37]) give uncertain conclusions about the fraction of the halo dark matter in the form of MACHOs, ranging from about 20% for $0.1-1\ M_\odot$ MACHOs to the possibility of explaining the detected events simply by self-lensing (see e.g. [38, 39, 40, 41, 42, 43]).

[5] Somewhat similar scenarios have been also proposed in [47, 48, 49, 50]. Models in which the galactic dark matter is in baryonic form and distributed in a thin disk have also been proposed along with many observational consequences [51, 52].

issue to be investigated. The rotation of the galactic halos, indeed, is clearly related to the formation scenario of galaxies. In the standard collapse model (see e.g. [55]) both the halo and disk of galaxies derive from the same population. The rotation of the outer halo should be, in this case, aligned with the disk angular momentum. On the contrary, in a hierarchical formation scenario, structures arriving later in the outer halo should have a minor connection to the disk. Therefore, it is evident that information on the galactic halo rotation provide key insights about the formation history of galaxies. Nevertheless, it is important to stress that testing for the rotation even of the closest galaxy (M31) halo is still beyond our reach [56] (see also [57]).

The first attempt of using the 7-year WMAP data [58] in the three bands W (94 GHz), V (61 GHz), and Q (41 GHz) to map in microwaves both the disk and halo of the M31 galaxy is provided in [59] [6]. To reveal the different contributions by the M31 disk and halo, the region of the sky towards the M31 galaxy has been divided into several concentric circular areas as shown in Fig. 1 in [59].

The M31 disk does contain gas observed mainly at 21 cm wavelength (but also in the IR) up to a distance of about 40 kpc from the galactic center. It is also well known that the M31 disk rotate with a speed of about 250 km s^{-1} and this has been clearly shown also by the velocity maps provided in [60, 61]. In [59] a temperature asymmetry along the direction of the M31 rotation has been observed for the first time also in microwaves with a maximum of $\simeq 130$ μk/pixel at about 20 kpc from the M31 center. This temperature asymmetry is very likely induced by the Doppler shift effect due to the M31 disk rotation speed. The robustness of this result has been tested by considering 500 randomly distributed control fields in the three WMAP bands and also by simulating 500 sky maps from the best fit cosmological parameters. Both procedures give comparable results and imply that there is less than $\simeq 2\%$ probability that the signal is due to a random fluctuation of the CMB signal. An analogous study has been also conducted in the same paper towards the M31 halo within 20^0 (about 240 kpc from the M31 center). We found also towards the M31 halo a CMB temperature asymmetry up to about 120 kpc with a peak temperature contrast of about 40 μK/pixel. Although the confidence level of the signal, if estimated purely statistically (i.e. with 500 control fields and 500 simulated sky maps), is not high (we find, indeed, that there is a probability of less than about 30% that the detected temperature asymmetry in the M31 halo is due to a random fluctuation of the CMB signal) [7], the geometrical structure of the temperature asymmetry in the three bands point towards a real effect modulated by the rotation of the M31 halo.

We point out once more that the use of three WMAP bands is important for revealing the role of the contribution of the Galactic foregrounds since each emission mechanism contributes differently in each band. The fact that the temperature contrast seems present in all three bands and is more or less the same in each band up to about $10^0 - 11^0$ (about 120 kpc from the M31 center) indicates that the foregrounds are far weaker than the effect. A size of about 120 kpc corresponds to the typical size inferred for the dark matter halos around massive galaxies and might open the possibility of a new way of studying these systems, both galactic disks and halos, at microwave wavelengths. In any case, a careful analysis of the Planck data that should be released shortly should allow either to prove or disprove our main results.

[6] The use of three WMAP bands is important in revealing the possible contribution of the Galactic foregrounds since dust, free-free, and synchrotron emission contributes in a different way in each band. We also remind that the band least contaminated by the synchrotron radiation of the Galaxy is the W-band, which also has the highest angular resolution.

[7] Actually, if one takes the direction of rotation of the M31 disk into account, such a probability reduces (by using the theorem of the composite probability) by a factor of two. So that one can conclude that there is a probability of less than about 15% that the detected temperature asymmetry in the M31 halo is due to a random fluctuation of the CMB signal.

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3. Discussion

As clear from the discussion above, the detected temperature asymmetry for the M31 disk is fairly clear in all WMAP bands, and is also expected due to the foreground emission of the M31 disk modulated by the Doppler shift induced by the disk rotation. Incidentally, the M31 galaxy has been recently detected by the Planck observatory [62] [8], whereas it did not appear in the WMAP list. These are all reasons to expect that the particular effect we discuss here can be studied more accurately with Planck data.

As for the M31 halo, we have shown that, although less evident than for the M31 disk, there is less than about 20% probability that the detected temperature asymmetry at a galactocentric distance ~ 50 kpc comes from a random fluctuation of the CMB signal. [9]

If one assumes that this temperature asymmetry in the M31 halo relies in the M31 itself and is related to the M31 halo rotation, a natural question that arises is about the origin of this effect. In all generality, four possibilities may be considered: (*i*) free-free emission; (*ii*) synchrotron emission; (*iii*) Sunyaev-Zel'dovich (SZ) effect; and (*iv*) cold gas clouds populating the M31 halo. The first three effects assume the presence of a rather hot plasma in the halo of M31. Although this hot plasma has not been detected yet, one can assume that a certain amount of this plasma can populate the M31 halo (spiral galaxies are believed to have much less hot gas than ellipticals) and may rotate with a certain speed. Free-free emission arises from electron-ion scattering while synchrotron emission comes mostly from the acceleration of cosmic-ray electrons in magnetic fields. Both effects give rise to a thermal emission with a rather steep dependence on the frequency [64] that therefore should give a rather different temperature contrast in the three WMAP bands. The absence of this effect indicates that the contribution from possibilities (*i*) and (*ii*) should be negligible. In the case of (*iii*), even for typical galaxy clusters with diffuse gas much hotter than that possibly expected in the M31 halo, the rotational effect produces a temperature asymmetry of at most a few μK pixel^{-1}, depending on the rotational velocity and the inclination angle of the rotation axis [65], that is much less than that observed towards the M31 halo. Actually, a possible temperature asymmetry in the CMB data towards the M31 halo as a consequence of the existence of a population of cold gas clouds in its halo was predicted in [66] - possibility (*iv*). Indeed, if the halo of the M31 galaxy would contain gas clouds, one expects them to rotate along the disk rotation (even if, perhaps, more slowly), and thus there should be a Doppler shift inducing a temperature anisotropy ΔT between one side of the M31 halo and the other with respect to the rotation axis perpendicular to the disk. In the case of optically thin halo clouds the Doppler induced temperature asymmetry would be $\Delta T/T_r \simeq 2vS\bar{\tau}/c$, where $T_r \simeq 2.725$ K is the CMB temperature, v is the M31 averaged rotation speed, $\bar{\tau}$ the averaged cloud optical depth over the frequency range ($\nu_1 \leq \nu \leq \nu_2$) of a certain detection band, and S the cloud filling factor, i.e. the ratio of filled (by clouds) to total projected sky surface in a given field of view. In the case of optically thick gas clouds instead one has $\Delta T/T_c \simeq 2vS/c$, where T_c is the cloud temperature [10].

In [66] we concentrated mainly on the optically thick option and, as a suggested test for the proposed model (see also [67, 68]), made a rough estimate [11] of the expected temperature asymmetry between the two opposite sides of the M31 halo as $\Delta T/T_r \simeq 2 \times 10^{-5}\bar{\tau}$ that implies

[8] However, there is no mention of any temperature asymmetry in the M31 disk in that paper.

[9] We also mention that the number and the temperature profile of radio sources in CMB maps [63] excludes their significant contribution in the effect under study.

[10] Note, however, that cold gas clouds in galactic halos are not expected to be optically thick at microwave wavelengths.

[11] We estimated, based on our model, S to be about 1/25 and assumed a halo rotation speed about 100 km s^{-1}. By the way, this value for S is not far from that coming from recent observations of HVCs in M31 presented in Fig. 1 in [14]. Indeed it turns out that S can be parameterized as $S \simeq 2.1\exp[-r/(12kpc)]$, so that $S \simeq 0.05$ at about 40 kpc from the M31 center. We emphasize, however, that this limit has to be considered as a lower limit to the true value of S since it only comes from considering the observed HVCs in the M31 halo.

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a temperature asymmetry about 50 μK for $\bar{\tau} \lesssim 1$, that is very close to the value recently found in [59].

Before closing this Section we would like to mention that one of the most serious problems associated with the presence of cold gas clouds in galactic halos is that of explaining their mere dynamical stability. As a matter of fact, isothermal perfect gas clouds without fixed boundaries are unstable with respect to the gravothermal catastrophe on time scales of a few crossing times. Generally speaking, the outcome of the gravitational collapse of a gas cloud is the formation of a dense central core (see e.g. [69]). At the beginning, the evolution is almost isothermal (due to the low optical depth of the gas cloud) but, when opacity exceeds unity, the central temperature and pressure rapidly increase, leading to star formation. However, halo cold gas clouds may mostly succeed in avoiding collapse since in low temperature and low opacity conditions, collapse may lead to the formation of solid/liquid H_2 (below about 14 K) and to the formation of a temperature inverted gas cloud with a condensed cold core. This new physical ingredient provides the possibility of stabilizing these cold gas clouds. Such loosely bound cold clouds could form a gas reservoir in galaxy halos and behaves as a collisionless ensemble of matter. Incidentally, these cold cores might also evaporate due to ambient heating, but they can leave for Gyrs in the clod and low excitation environment such as those expected in galactic halos (for further details see also [70, 71]). Interestingly enough, cosmic rays and energetic photons (for example those in the UV band of the electromagnetic spectrum) might cause ionization in the solid molecular hydrogen leading to the formation of H_6^+ and $(HD)_3^+$. Very recently, it has been shown [72] that the so-called unidentified infrared (UIR) bands, usually thought to be related to large molecules such as polycyclic aromatic hydrocarbons, may instead be produced by $(HD)_3^+$ and H_6^+ in solid form, thus showing that solid H_2 may indeed be abundant in quiet astrophysical environments and opening a new way of searching for cold gas clouds.

4. Concluding remarks

As mentioned earlier, it is likely that there are no grounds to assume that a unique solution may solve the hidden baryon problem. It is instead plausible that it is a composite problem reflecting the diversity of astrophysical conditions.

For example, globular clusters are mostly composed of baryons and no evidence for non-baryonic mass is present in these objects. Thus, baryons are well separated from non-baryonic dark matter in the formation process of these structures. On the galaxy cluster scale most baryons are in the form of a hot X-ray emitting gas while in the inter-galactic medium most baryons might be in the form of a warm-hot gas.

The wealth of data especially in the last decade shows that there is good evidence for the presence in the halos of spiral galaxies of gas in all gaseous phases: neutral, warm atomic, and hot X-ray emitting gas [73]. Atomic gas (often identified as HVCs) is observed in the radio band (particularly at 21 cm) and through absorption lines towards field stars and quasars. The hot gas may be detected in X-rays but, unfortunately, searches for cold gas clouds in galactic halos are more problematic. Various attempts have been undertaken to detect such clouds as searching for the presence of a gamma-ray halo [74, 75], stellar scintillations [76, 77], obscuration events towards the LMC [78], ortho-H_2D^+ line at 372 GHz [79], and extreme scattering events in quasar radio-flux variations [50]. All these searches have given no clear indication of cold gas cloud presence in galactic halos, but these searches are going on using more and more sensitive facilities and new developments, such as searching for the vibrational transition lines produced by $(HD)_3^+$ and H_6^+ in solid form. Therefore, the issue of a realistic estimate of the amount of baryonic mass in galactic halos and their size does remain open and a new perspective in this research can be given by investigating it in microwaves following [59].

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